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Towards Prediction of Environmental Arctic Change

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Abstract

Our main objective is to use models of the coupled ice-ocean Arctic environment to understand the past and present sea ice and ocean states and to predict future scenarios of environmental change in the Arctic Ocean. To meet this objective we have developed a coupled ice-ocean model of the sea ice covered northern hemisphere at 9-km and 45-level grid. The model has been spun up for 48 years. Three 24-year experiments have been completed following the spinup, all forced with realistic 1979–2002 ECMWF data but with a different surface temperature and salinity restoring times. Results from these integrations are compared to each other and to sea ice data available over this period to address the growing need for understanding the recent warming and the subsequent decrease of the Arctic Ice Pack during the late 1990s and 2000s.

1. Introduction

Recent studies suggest that the Arctic Ocean is a variable system experiencing major regime shifts at time scales from several years to decades due to the changing atmospheric dynamics and/or to exchanges with the lower latitude oceans. The Arctic Ocean has experienced an intensified warming during the 1990's and into the 2000's, as observed from satellites, submarines and other *in situ* measurements (e.g., Comiso, et al., 2003, Rothrock et al., 2003, Serreze, et al., 2003). Some of the critical signatures of recent change include an increased heat flux into the Arctic Ocean and a significant reduction in thickness and extent of the Arctic perennial sea-ice cover, which have important operational implications to the US Navy. If continued, this warming trend will not only significantly affect global climate but it will also change the strategic/economic importance of the Arctic Ocean through its use for commercial shipping routes and increased exploration of natural resources. What is more important, according to some global climate model predictions, an 80% decrease of the Arctic ice pack can occur within the next 50 years or so. On the other hand, analyses based on both observations and models suggest at least two regimes in the arctic atmospheric circulation directly influencing sea-ice conditions and the distribution and fluxes of freshwater and Atlantic Water. Whether these regimes are cyclic, driven by coupling with lower latitudes, or part of a trend related to global changes is yet to be determined. Regardless of the cause, the reduction or absence of sea ice cover in the Arctic Ocean will require significant tactical and logistics modifications in the Navy to allow existing missions to successfully operate in a partly and/or seasonally sea ice covered environment.

2. Problem and Methodology

Before making predictions of future change in the Arctic Ocean, proper understanding of recent variability in the region is necessary. The ongoing analysis implies that existing global climate predictions might have large errors due to both insufficient model resolution as well as 'missing' physics. We find that the sea ice response to variable atmospheric regimes strongly depends on the model representation of sea ice and the upper ocean conditions before and during the time of change. However, the problem is that sea ice and ocean models used in global climate studies are typically configured at fairly coarse resolution (>1°) and they use crude parameterizations of the thermodynamic and dynamic processes that determine the ice thickness and extent and the upper ocean conditions. These limitations have been so far significant enough to make it rather difficult for such models to realistically reproduce the past and present variability in the Arctic Ocean, which reflects on their skill in predicting future changes.

Regional, high-resolution modeling is an alternative and complementary approach to climate studies, which takes advantage of recent advancements in sea ice and ocean modeling and the availability of powerful parallel supercomputers for high-resolution environmental modeling. This approach can also be considered as a

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temporary one to advance the science of the complex air-sea-ice interactions in a region before computational resources become available for global model configurations at similar grid resolutions. The main challenges in modeling the Arctic Ocean and its sea ice include realistic representation of the physical processes specific to polar regions and resolution of small-scale features such as narrow boundary currents (0(100km)), the Rossby radius of deformation (0(10km)), and the bottom bathymetry and land geometry controlling the physics.

Highly parallel regional models optimized for modern computer architectures exist, which incorporate state-of-the-art physics into high-resolution numerical grids. However, regional ocean circulation models commonly use some type of restoration to climatological surface temperature and salinity data to compensate for air-sea heat and freshwater fluxes, which are especially poorly known in the polar regions. There are reasonable concerns that this surface restoration may limit the ocean's ability to realistically interact with atmospheric forcing and sea ice cover at time scales from years to decades. Here we present results, which provide insights on the impact of surface restoration of temperature and salinity in ocean models on the representation of sea ice conditions and their multi-decadal variability.

3. Results

We have developed a coupled ice-ocean model of the sea ice covered northern hemisphere at 9-km and 45-level grid (Maslowski and Lipscomb, 2003, Maslowski, et al., 2004). The sea ice model includes a parallel version of the Hibler's dynamic model with viscous-plastic rheology (Hibler, 1979) and the thermodynamic model based on (Parkinson and Washington, 1979) with the zero-layer approximation for heat conduction through the ice (Semtner, 1976). It is coupled to a regional adaptation of the Los Alamos National Laboratory Parallel Ocean Program (POP) with the free-surface approach (Dukowicz and Smith, 1994) and unsmoothed realistic bathymetry. The model has been integrated for 48 years in a spin up mode using climatological and 1979–1981 atmospheric forcing from ECMWF. Three 24-year experiments have been completed following the spinup, all forced with 1979–2002 ECMWF data but with a different temperature and salinity restoring time at the surface, represented by a top 5-meter thick ocean layer. Daily-averaged annual cycles of salinity and temperature at river mouths Yukon, Mackenzie, Ob, Yenisey, Lena, Katanga, Dvina, Pechora, Kolyma, and Indigirka are prescribed as a function of river discharge. The restoring at the ocean surface layer to monthly Polar Science Center Hydrographic Climatology (PHC, Steele, et al., 2000) temperature and

salinity values is applied as a correction term to the explicitly calculated heat and buoyancy fluxes between the ocean and overlying atmosphere or sea ice. The restoring time scales for temperature (T_{surf}) and salinity (S_{surf}) for each 24-year experiment are listed in Table 1. Each experiment required ~760,000 processor-hours of Cray T3E available at the Arctic Region Supercomputer Center (ARSC) and the USACE Engineering Research and Development Center (ERDC).

Table 1. Restoration time for surface temperature and salinity for each experiment

Experiment	T_{surf}(days)	S_{surf}(days)
Case1	30	30
Case2	120	365
Case3	365	10^{15}
Case4	10^{15}	10^{15}

Results from these integrations are compared to each other and to the sea ice extent and thickness data available over this period to address the concerns about use of surface restoration. They also contribute to the growing need for understanding the recent warming of the ocean and the subsequent decrease of the Arctic Ice Pack during the late 1990s and 2000s.

The sea ice thickness distribution in September of 1982 for each case is shown in Figure 1. These results do not differ from each other too much, except along the ice edge in marginal seas (e.g., Kara, Greenland and Siberian seas), since each experiment has only completed less than four years with different surface restoration time. However, the difference distributions (Figure 2) suggest a decreasing trend in the central Arctic ice thickness with the increased restoration time (i.e., weakening restoring). Relatively small positive thickness differences up to 0.5 m indicate thicker ice in a case being subtracted from (i.e., Case1 or Case2) compared to a case being subtracted. It is worth noting that the difference between the Case2 and Case4 produces larger positive anomalies than the difference between the Case1 and Case4, which does not support the earlier conclusion that weaker restoring produces less (thinner) ice in the central Arctic.

Ten years later in September 1992 (Figure 3), there is generally more and thicker sea ice throughout the Arctic Ocean. However, the general pattern of sea ice thickness distribution is still rather similar for all three cases considered (note that the color legend is the same in Figures 1, 3, and 5). The mean sea ice thickness in the central Arctic is over 3.0 m in 1992 compared to 2.5–3.0 m in 1982. Significantly thicker ice cover (up to 5 m) is present along the northern Canadian Archipelago and northern Greenland, which is generally about 1 m more

than in 1982 in those areas. The early 1990s is the time of significant warming of the Atlantic layer (Morison, et al., 1998; Maslowski, et al., 2000; Maslowski, et al., 2001), which does not appear to have an effect on the sea ice cover yet.

The distribution of ice thickness differences in 1992 (Figure 4) shows larger amplitudes both positive and negative. The comparison of Case1 with Case2 indicates that ice was thinner in the former case almost everywhere in the Arctic Ocean except to the north of Fram Strait. There is up to 2-m of sea ice deficit (i.e., less ice in Case1) in the Russian marginal seas, southeastern Beaufort Sea, northern Canadian Archipelago, and in the northern Baffin Bay, where the North Water Polynya commonly occurs. The general trend in the three cases is that sea ice is thinner/thicker in/along the center/perimeter of the Arctic Ocean with the decreased restoration. However, the largest differences in sea ice thickness are shown between Case 2 and Case3 as in 1982.

In 2002 (Figure 5), the mean ice thickness in the central Arctic Ocean has decreased dramatically to below 2.0 m and many marginal seas are ice-free in September. These results are in qualitative agreement with the observations (Serreze, 2003), suggesting the record minimum ice extent and area in the summer of 2002. The thickest ice cover to the north of the Canadian Archipelago and Greenland is now not much thicker than 3.0 m. Taking into account that this is 24 years later since the beginning of each integration, it is remarkable how similar the three considered cases still are. One can argue that the simulated differences of 0–0.5 m in sea ice thickness distribution (Figure 6) due to different restoration time are insignificant after 24 years compared to typical errors in the sea ice extent and thickness distribution in GCMs.

4. Significance to DoD

Our research implies that many existing predictions of environmental change in the Pan-Arctic region might have large errors due to insufficient model resolution to account for details of bathymetry, circulation, and exchanges with adjacent oceans as well as inaccuracy of atmospheric forcing. Those errors are possibly much larger than those introduced by the restoration of surface ocean temperature and salinity to climatological data. Our results also indicate that the surface ocean restoring does not significantly affect the sea ice cover and thickness distribution. The regional modeling approach can provide quite accurate predictions of ice edge, marginal ice zone, and deformation in the Arctic Ice Pack, should the improved initial and forcing data become available. This includes the realistic and time-dependent precipitation and runoff data to reduce the effect of surface ocean restoration to climatological fields.

5. Systems Used

Two experiments (Case1 and Case2) have been completed using the Cray T3E at ARSC and one experiment (Case3) using the Cray T3E at ERDC. The Case4 is being currently completed at ARSC. All computer resources have been provided by the DoD High Performance Computer Modernization Program (HPCMP) via a Challenge Project entitled: Towards Predicting Scenarios of Environmental Arctic Change (TOPSEARCH).

## 6. CTA

Climate/Weather/Ocean Modeling and Simulation (CWO)

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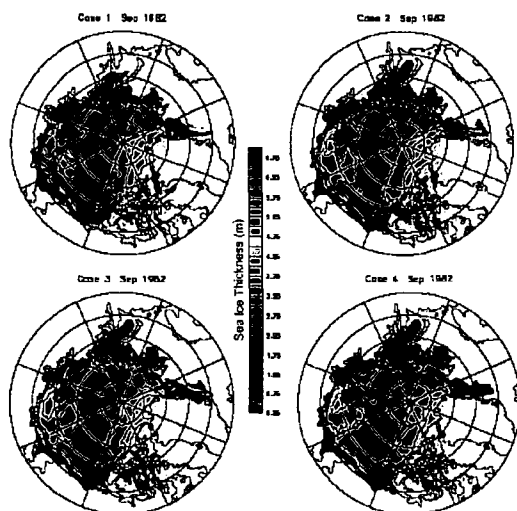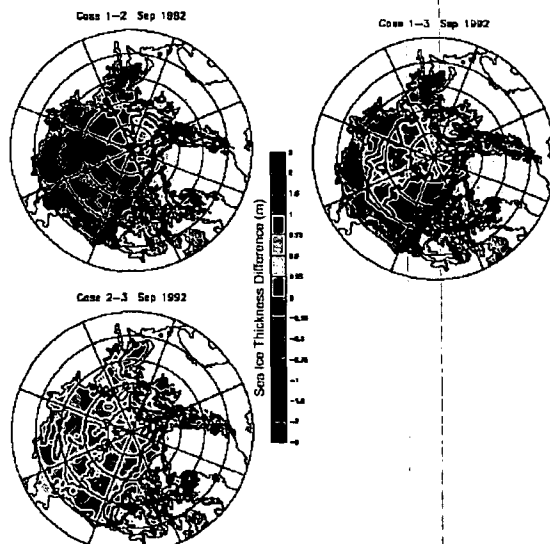
Figure 1. Sea ice thickness distribution [m] for September 1982 from the Case1 (top- left), Case2 (top-right), Case3 (lower left) and Case4 (lower- right). Contour interval is 0.5 m.
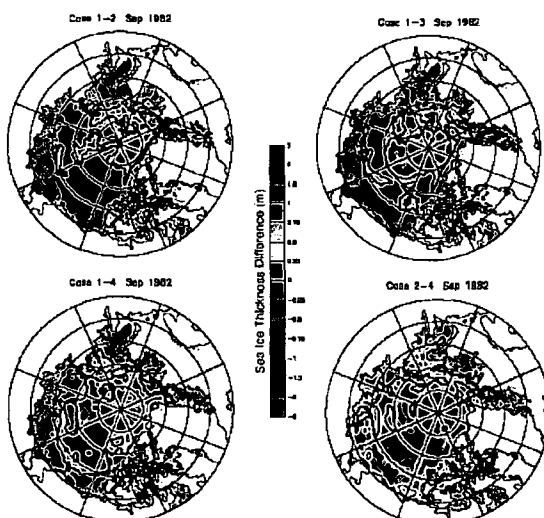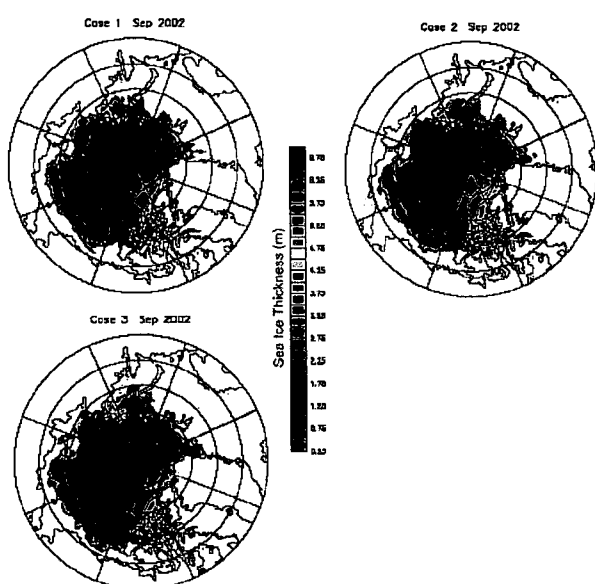
Figure 2. Differences [m] in sea ice thickness distribution in September 1982 for Case1–Case2 (top-left), Case1–Case3 (top-right), Case1–Case4 (lower-left), and Case2–Case4 (lower-right). Thick solid line separates positive from negative anomalies.
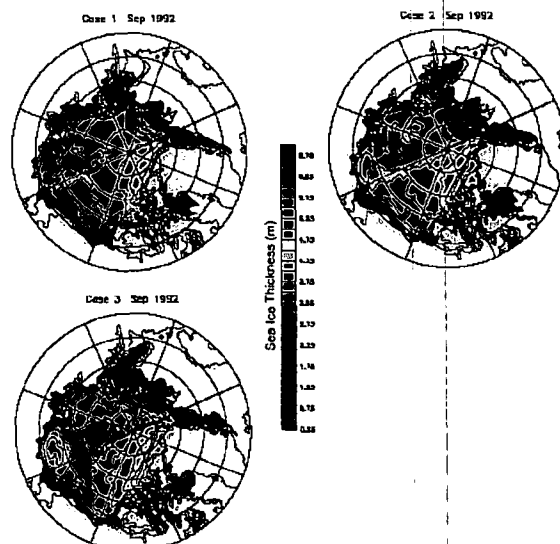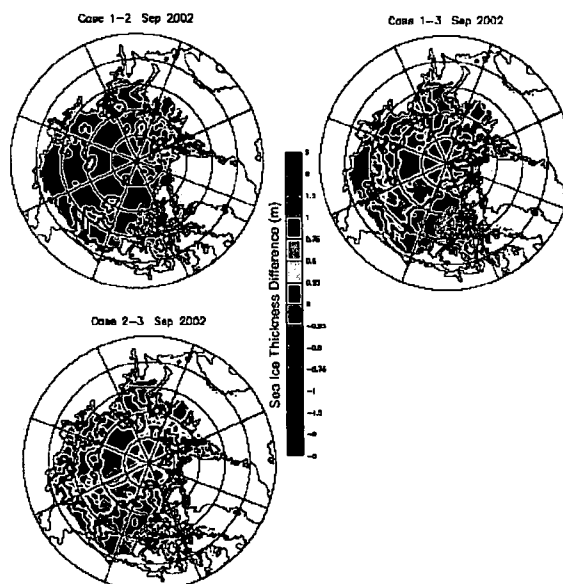
Figure 3. Sea ice thickness distribution [m] in September 1992 for the Case1 (top-left), Case2 (top-right) and Case3 (bottom). No results are available passed 1985 for the Case4 at this time.

Figure 4. Differences [m] in sea ice thickness distribution in September 1992 for Case1–Case2 (top-left), Case1–Case3 (top-right), and Case2–Case3 (bottom)

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Figure 5. Sea ice thickness [m] distribution in September 2002 for the Case1 (top-left), Case2 (top-right) and Case3 (bottom)

Figure 6. Differences [m] in sea ice thickness distribution in September 2002 for Case1–Case2 (top-left), Case1–Case3 (top-right), and Case2–Case3 (bottom)